V. "On Heat Conduction in Highly Rarefied Air." By WILLIAM CROOKES, F.R.S. Received November 18, 1880.

The transfer of heat across air of different densities has been examined by various experimentalists, the general result being that heat conduction is almost independent of pressure. Winkelmann ("Pogg. Ann.," 1875–76) measured the velocity of cooling of a thermometer in a vessel filled with the gas to be examined. The difficulty of these experiments lies in the circumstance that the cooling is caused not only by the conduction of the gas which surrounds the cooling body, but that also the currents of the gas and, above all, radiation play an important part. Winkelmann eliminated the action of currents by altering the pressure of the gas between 760 and 1 millim. (with decreasing pressure the action of gas currents becomes less), and he obtained data for eliminating the action of radiation by varying the dimensions of the outer vessel. He found that, whereas a lowering of the pressure from 760 to 91·4 millims. there was a change of only 1·4 per cent. in the value for the velocity of cooling, on further diminution of the pressure to 4·7 millims. there was a further decrease of 11 per cent., and this decrease continued when the pressure was further lowered to 1·92 millim.

About the same time Kundt and Warburg ("Pogg. Ann.," 1874, 5) carried out similar experiments, increasing the exhaustion to much higher points, but without giving measurements of the pressure below 1 millim. They enclosed a thermometer in a glass bulb connected with a mercury pump, and heated it to a higher temperature than the highest point at which observations were to be taken; then left it to itself, and noted the time it took to fall through a certain number of degrees. They found that between 10 millims. and 1 millim. the time of cooling from 60° to 20° was independent of the pressure; on the contrary, at 150 millims. pressure the rate was one-and-a-half times as great as at 750 millims. Many precautions were taken to secure accuracy, but no measurements of higher exhaustions being given the results lack quantitative value.

It appears, therefore, that a thermometer cools slower in a so-called vacuum than in air of atmospheric pressure. In dense air convection cnrrents have a considerable share in the action, but the law of cooling in vacua so high that we may neglect convection, has not to my knowledge been determined. Some years ago Professor Stokes suggested to me to examine this point, but finding that Kundt and Warburg were working in the same direction it was not thought worth going over the same ground, and the experiments were only

tried up to a certain point, and then set aside. The data which these experiments would have given are now required for the discussion of some results on the viscosity of gases, which I hope to lay before the Society in the course of a few weeks; I have therefore completed them so as to embody the results in the form of a short paper.

An accurate thermometer with pretty open scale was enclosed in a $1\frac{1}{2}$ inch glass globe, the bulb of the thermometer being in the centre, and the stem being enclosed in the tube leading from the glass globe to the pump.

Experiments were tried in two ways:—

I. The glass globe (at the various exhaustions) was immersed in nearly boiling water, and when the temperature was stationary it was taken out, wiped dry, and allowed to cool in the air, the number of seconds occupied for each sink of 5° being noted.

II. The globe was first brought to a uniform temperature in a vessel of water at 25°, and was then suddenly plunged into a large vessel of water at 65°. The bulk of hot water was such that the temperature remained sensibly the same during the continuance of each experiment. The number of seconds required for the thermometer to rise from 25° to 50° was registered as in the first case.

It was found that the second form of experiment gave the most uniform results; the method by cooling being less accurate, owing to currents of air in the room, &c.

The results are embodied in the following table:—

(Rate of Heating from 25° to 50°.)

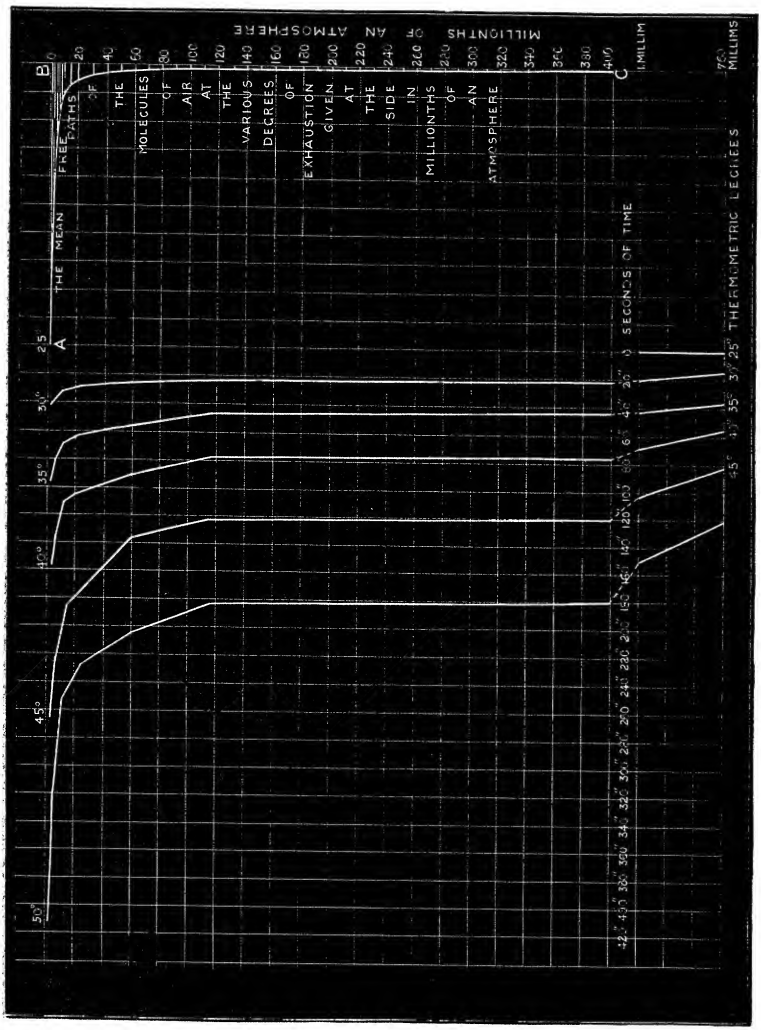
Table I.

Pressure.	Temperature.	Seconds occupied in rising each 5°.	Total number of seconds occupied.
760 millims.	25°	0	0
	25 to 30	15	15
	30 35	18	33
	35 40	22	55
	40 45	27	82
	45 50	39	121
1 millim.	25°	0	0
	25 to 30	20	20
	30 35	23	43
	35 40	25	68
	40 45	34	102
	45 50	48	150

Pressure.		Temperature.		Seconds occupied in rising each 5°.		Total number of seconds occupied.
620 M.*	..	25°	..	0	..	0
		25 to 30	..	20	..	20
		30 35	..	23	..	43
		35 40	..	29	..	72
		40 45	..	37	..	109
		45 50	..	33	..	162
117 M.	..	25°	..	0	..	0
		25 to 30	..	23	..	23
		30 35	..	23	..	46
		35 40	..	32	..	78
		40 45	..	44	..	122
		45 50	..	61	..	183
59 M.	..	25°	..	0	..	0
		25 to 30	..	25	..	25
		30 35	..	30	..	55
		35 40	..	36	..	91
		40 45	..	45	..	136
		45 50	..	67	..	203
23 M.	..	25°	..	0	..	0
		25 to 30	..	28	..	28
		30 35	..	33	..	61
		35 40	..	41	..	102
		40 45	..	55	..	157
		45 50	..	70	..	227
12 M.	..	25°	..	0	..	0
		25 to 30	..	30	..	30
		30 35	..	37	..	67
		35 40	..	41	..	108
		40 45	..	58	..	166
		45 50	..	86	..	252
5 M.	..	25°	..	0	..	0
		25 to 30	..	38	..	38
		30 35	..	43	..	81
		35 40	..	54	..	135
		40 45	..	71	..	206
		45 50	..	116	..	322

* M = millionth of an atmosphere.

Pressure.	Temperature.	Seconds occupied in rising each 5°.	Total number of seconds occupied.
2 M. ..	25° ..	0 ..	0
	25 to 30 ..	41 ..	41
	30 35 ..	51 ..	92
	35 40 ..	65 ..	157
	40 45 ..	90 ..	247
	45 50 ..	165 ..	412

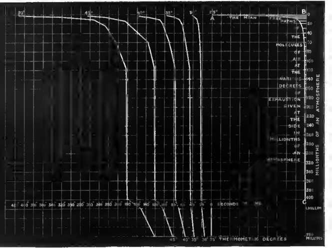


I have embodied these results in the preceding diagram. The ordinates represent the number of seconds occupied during the rise of each 5°, starting from 25°; the abscissæ represent the pressure. The lower portion gives the total variation in time between pressures of 760 millims. and 1 millim. The upper and larger portion of the diagram gives the abscissæ in millionths of an atmosphere. At the right side of the diagram, in the space A B C, I have drawn a series of horizontal lines increasing in length from 0·25 millim. at 400 M., to 100 millims. at 1 M. These show the actual lengths of the mean free path of the molecules of air at the degrees of exhaustion to which they are opposite.* The parallelism between the curves formed by joining the ends of these horizontal lines and the curves representing the rate of cooling is sufficiently close to justify the inference that they are associated phenomena.

There are two ways in which heat can get from the glass globe to the thermometer—(1) By radiation across the intervening space; (2) by communicating an increase of motion to the molecules of the gas, which carry it to the thermometer. It is quite conceivable that a considerable part, especially in the case of heat of low refrangibility, may be transferred by "carriage," as I will call it to distinguish it from convection which is different, and yet that we should not perceive much diminution of transference, and consequently much diminution of rate of rise with increased exhaustion, so long as we work with ordinary exhaustions up to 1 millim. or so. For if, on the one hand, there are fewer molecules impinging on the warm body (which is adverse to the carriage of heat), yet on the other the mean length of path between collisions is increased, so that the augmented motion is carried further. The number of steps by which the temperature passes from the warmer to the cooler body is diminished, and accordingly the value of each step is increased. Hence the increase in the difference of velocity before and after impact may make up for the diminution in the number of molecules impinging. It is therefore conceivable that it may not be till such high exhaustions are reached that the mean length of path between collisions becomes comparable with the diameter of the case, that further exhaustion produces a notable fall in the rate at which heat is conveyed from the case to the thermometer.

The above experiments show there *is* a notable fall, a reduction of pressure from 5 M. to 2 M., producing twice as much fall in the rate as is obtained by the whole exhaustion from 760 millims. to 1 millim. We may legitimately infer that each additional diminution of a millionth would produce a still greater retardation of cooling, so that in such vacua as exist in planetary space the loss of heat—which in that case would only take place by radiation—would be exceedingly slow.

* In the published diagram the lengths have been reduced by the engraver in the proportion of 8 to 3.


B
THE MEAN FREE PATHS OF THE MOLECULES OF AIR AT THE VARIOUS DEGREES OF EXHAUSTION GIVEN AT THE SIDE IN MILLIONTHS OF AN ATMOSPHERE
MILLIONTHS OF AN ATMOSPHERE
SECONDS
THERMOMETRIC DEGREES
45° 40° 35° 30° 25°
C
MILLIMS